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**VACUUM PUMPS AND SYSTEMS:  
A REVIEW OF CURRENT PRACTICE  
STUART GILES**

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ABSTRACT

A review of the fundamental characteristics of the many types of vacuum pumps and vacuum pumping systems may provide helpful perspective for the designer and user. The optimum operating range, relative cost, performance limitations, maintenance problems, system operating costs and similar subjects are discussed. Experiences from the thin film deposition, chemical processing, material handling, food processing and other industries as well as space simulation are used to support the conclusion and recommendations. Large space simulation systems have been and are discussed in detail by others at this, and other conferences and are therefore omitted from this paper.

INTRODUCTION

There is no one "best way" to design and build a space or altitude simulation vacuum pumping system but, as in any design project, an unbiased approach will provide optimum, cost effective results. This paper is only a brief summary of the characteristics of vacuum pumps and systems with some field experience examples and the full knowledge that it may over simplify the problems.

Vacuum pumps are grouped under DISPLACEMENT PUMPS AND ENTRAINMENT PUMPS to clarify the operating mode of each type. The former can run continuously as they compress the pumped gas and discharge it to atmosphere or to a backing pump. The latter traps and holds the pumped gas within the structure and therefore requires occasional regeneration or replacement of the gas trapping elements.

DISPLACEMENT PUMPS

OIL SEALED ROTARY TYPES (Fig. 1 & 2)

Vane and rotary piston sealed vacuum pumps are the most commonly used. Most pumps provide nearly constant throughput within their operating range.

Advantages include simplicity, reliability, and economy. Oil vapor discharge out the vent, particularly at high pressure and oil vapor backstreaming can be problems. Special configurations of this type of pump are available for corrosive gas pumping, high water vapor loads and operation at continuously high inlet pressures which will overload the common oil sealed pump designed to blank off in  $10^{-2}$  Pascal range or below.

#### ROOTS BLOWERS (Fig. 5)

Lobe type blowers (Roots) are useful as mechanical boosters when backed by an oil sealed pump. The blower is bypassed until a pressure between 3 and 50 Pascal (depending on design) is reached at which time the blower becomes a booster. Single stage units have good throughput to 100 Pascal range and blank-off in the low 0.1 range.

Staging can produce lower pressures. Lubrication is external to the vacuum pumping portion of the pump so that the Roots blower is not a source of backstreaming.

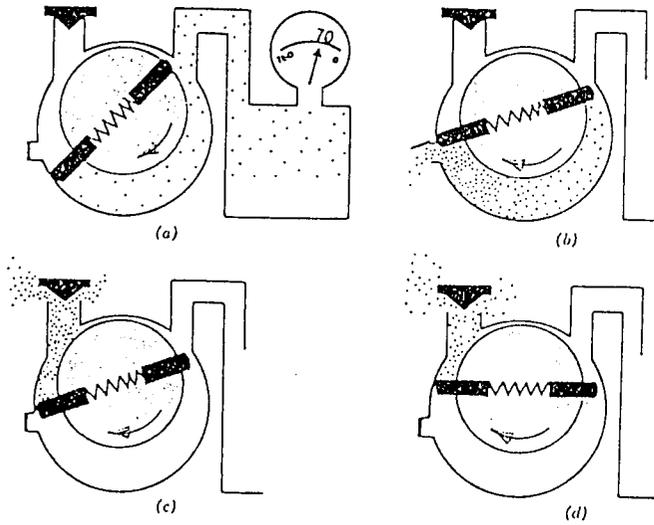
Roots blowers provide the increased pumping speed often required in the .1 to 40 Pascal range. They are a rugged, simple machine, reasonably resistant to dust and moisture. Backstreaming contamination is not usually a problem but can be if the oil sealed backing pump and the Roots blower are allowed to reach the molecular flow pressure range and the blower lobes become coated with oil from the backing pump. This can be prevented by automatically purging the backing pump with a dry gas to maintain viscous flow pressure level in the backing pump or by limiting the pressure by other means.

#### TURBOMOLECULAR PUMPS (Fig. 6)

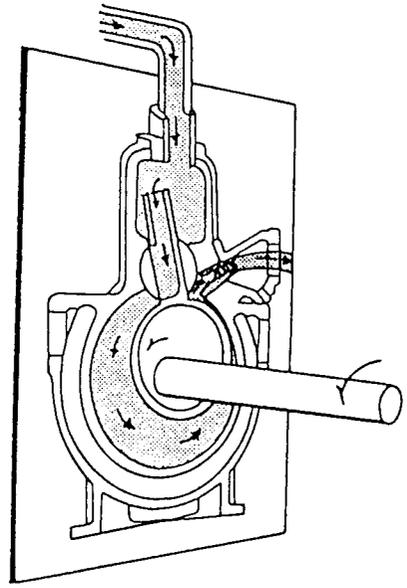
This type of vacuum pump is also a booster pump requiring a backing pump. Modern design permits this pump to be mounted with the inlet downward which reduces the chance of particulate matter entering and damaging the high speed turbine blades. Backstreaming possibility from this type of pump is very remote, contamination of oil from the backing pump, as discussed under Roots blowers, can produce backstreaming. Normal maintenance involves relubrication of the bearings after 5,000 to 10,000 hours of operation. Another advantage of the turbo pump is that overloading (high pressure suction) simply slows the pump; Roots pumps overheat and diffusion pumps backstream excessively if overloaded in this way.

The available sizes of this type of pump are limited so that they are not suitable for large vacuum system gas loads. Backstreaming of the mechanical backing pump oil can be reduced by a properly installed fore-line trap. The problem of syphoning oil from the backing pump after shut down into the turbo pump can be protected against by installing an automatic up-to-air valve.

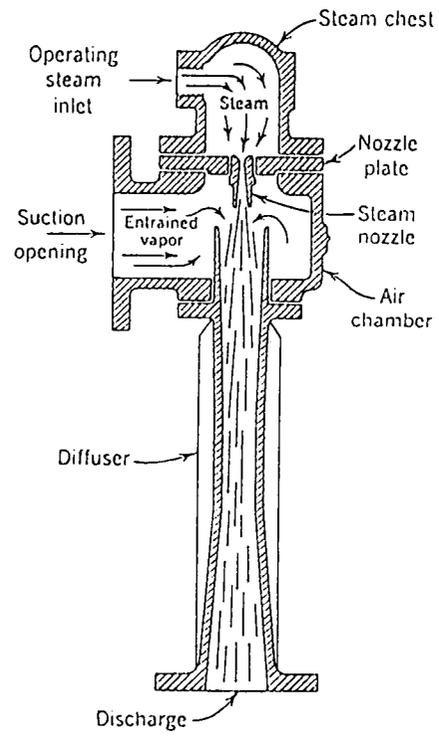
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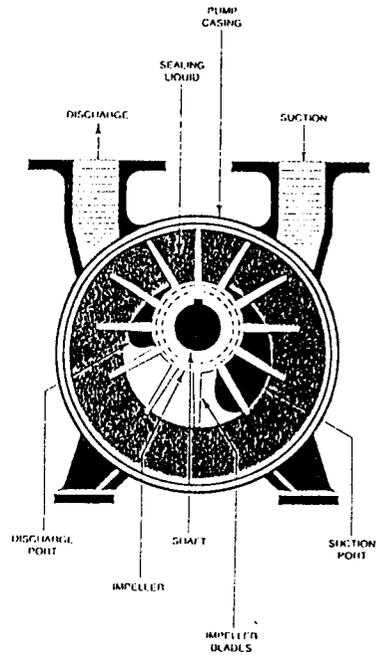
ROTARY VANE PUMP  
with gas-ballast FIG. 1



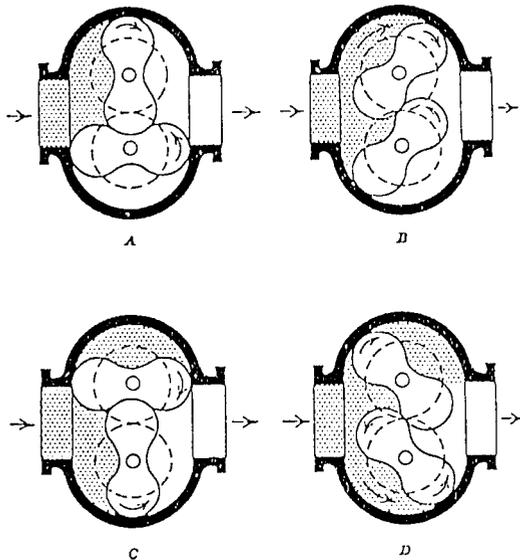
ROTARY PISTON PUMP  
FIG. 2



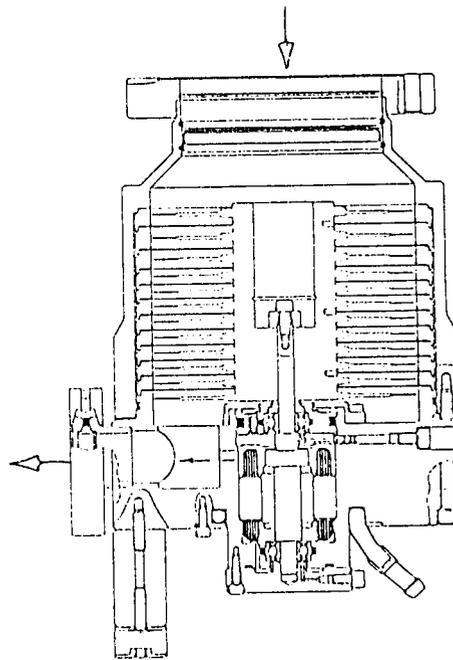
STEAM JET EJECTOR PUMP  
FIG. 3



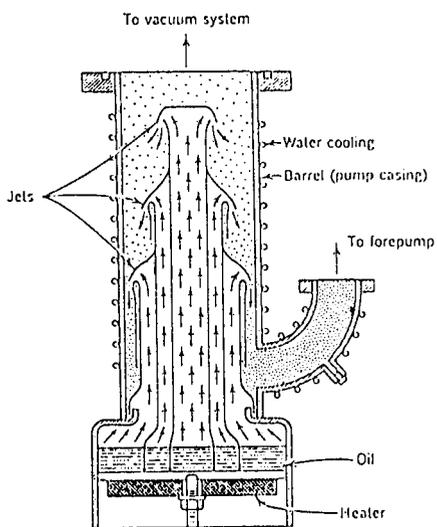
LIQUID RING PUMP  
FIG. 4



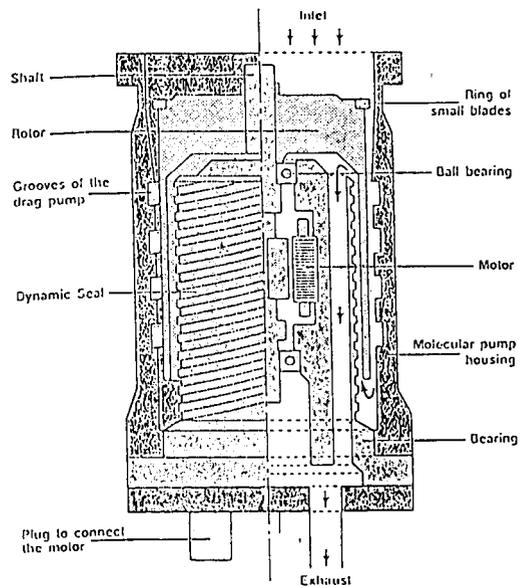
ROOTS TYPE BLOWER  
FIG. 5



TURBOMOLECULAR PUMP  
FIG. 6



DIFFUSION PUMP  
FIG. 7



MOLECULAR DRAG PUMP  
FIG. 8

## DIFFUSION PUMPS (Fig. 7)

Oil diffusion pumps are most commonly used for industrial processing in the  $10^{-1}$  to  $10^{-5}$  Pascal range. This type of pumping system is the lowest first cost for its pressure range, but cryogenic cold trapping must be used for processes sensitive to backstreamed oil. Diffusion pumps are available in a wide range of sizes.

Diffusion pumps are boosters and therefore require backing pumps which must be protected against backstreaming or syphoning the lubrication oil into the diffusion pump: this is the same problem as discussed under Roots pumps, except that the fore-line (discharge) pressure must be maintained below its tolerable level or the diffusion pump backstreaming will be excessive. It is advisable to use the same oil in the diffusion pump and backing pump if practical.

## ENTRAINMENT PUMPS

## CRYOGENIC PUMPS (Fig. 9)

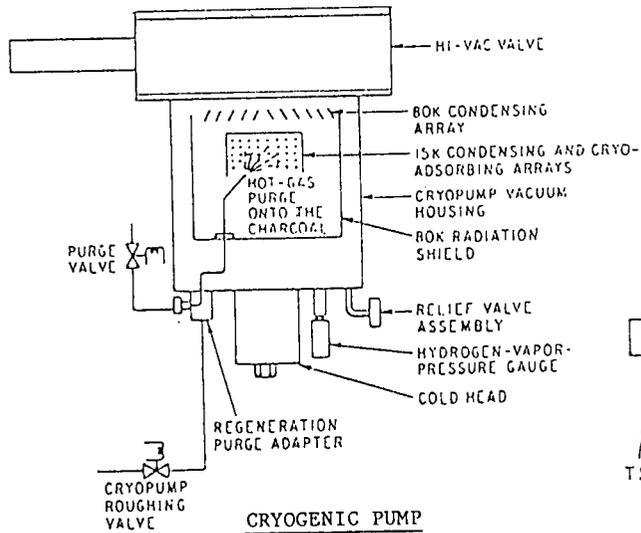
Cryo vacuum pumping is accomplished by a condenser and adsorber at cryogenic temperatures within or connected to the vacuum system. This type of pump is available in medium to large capacity sizes for most high vacuum applications. Because of its lack of contamination backstreaming and high pumping speed, it is popular for space simulation, manufacturing of thin film electronic devices and other sensitive processes. Regeneration is required and the possibility of power failure during operation should be considered in application design.

## IONIZATION PUMPS (Fig. 11)

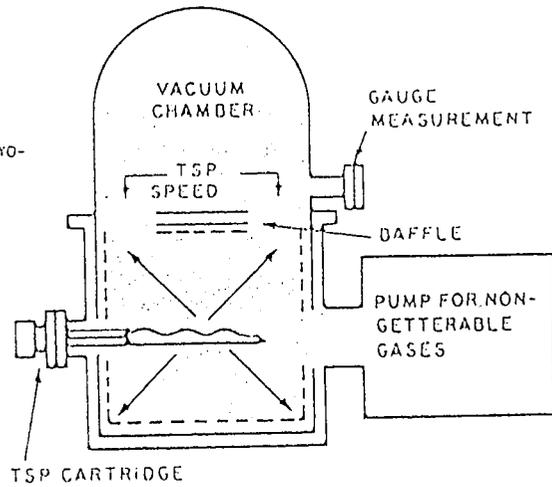
The ionization pump uses the Penning gage principle to collect gas within the pump structure by ionization and gettering. These work best below the  $10^{-2}$  Pascal range as pump life is relatively short at higher pressures. They find use in materials research and microminiature circuitry fabrication as well as space simulation. A primary advantage is that they provide a "dry vacuum environment" as there is no oil or other contaminant in the system. The roughing system may include a turbo or cryo pump and a well trapped two stage mechanical pump or an adsorption pump. Blank-off in the  $10^{-9}$  Pascal range is practical. The lack of traps and baffles, low power requirements and lack of need for  $LN_2$  are operating advantages particularly for long term life tests. A turbo or cryo pump may be necessary to pump the non-getterable gases in some applications.

The ion pump has a finite capacity and is relatively costly to rebuild when saturated; it cannot be regenerated as can a cryo or adsorption pump. Start-up pressure is critical and a used pump, if started at too high a pressure, may go into a glow discharge mode and release previous pumped gasses which can contaminate the chamber and the product under test or production.

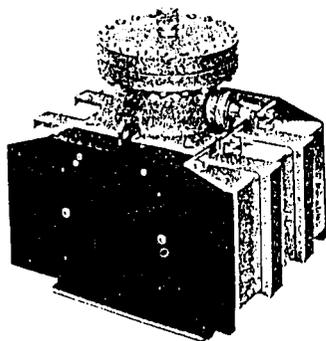
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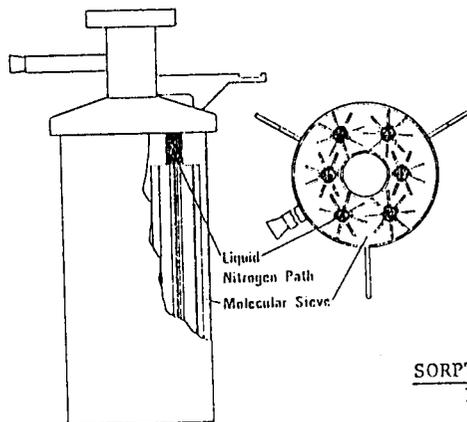
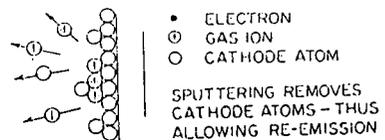
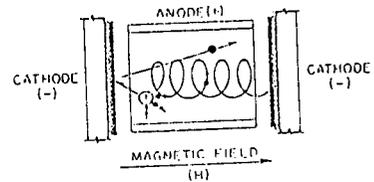
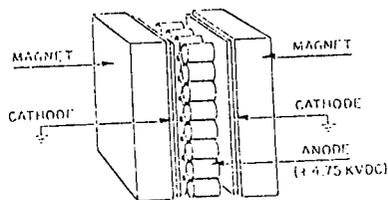
CRYOGENIC PUMP  
FIG. 9



TITANIUM SUBLIMATION SYSTEM  
FIG. 10



IONIZATION PUMP  
FIG. 11



SORPTION PUMP  
FIG. 12

## TITANIUM SUBLIMATION PUMP (Fig. 10)

Sublimation of titanium (or other active metal) onto a surface will getter some gases providing high pumping speeds. This technique supplements other pumping methods. The titanium source is replaceable and the reacted deposits may be mechanically removed. Combined with an ionization pump and the advantage of requiring no backing pump make it a completely closed system. A small turbo pump may be desirable to remove traces of non-getterable gases. No contamination occurs on power failure and only a small pressure rise takes place in a well-built system.

## SORPTION PUMP (Fig. 12)

Silica gel and other gas sorption materials, may be used to evacuate a chamber by chilling with liquid nitrogen or other refrigerant when the risk of backstreaming from a mechanical pump must be avoided. They are only practical for small systems, when cycle time is not a problem. Regeneration is frequently required and time consuming.

## OTHER TYPES OF VACUUM PUMPS

Centrifugal, diaphragm and reciprocating vacuum pumps are used for some industrial processes but not applicable to high vacuum work.

Liquid ring pumps are commonly used for dewatering and deaerating chemicals when solvents may be pumped. (Fig. 4). The required water supply and disposal may be a problem and the ultimate pressure is limited by the water vapor pressure.

The steam jet ejector (Fig. 3) is one of the oldest devices for producing vacuum in industrial applications. Staging of steam jets can produce ultimate pressures in the low  $10^{-3}$  Pascal range. Their primary application is for large degassing operations at 100 to 1.0 Pascal. The principal advantage is rugged simplicity: The most practical vacuum pump for pumping acids and caustics since they can be fabricated from almost any metal or even ceramics. Costs are very reasonable if "free" steam is available. If the steam generator, condenser, cooling water and accessory equipment are considered, costs are comparable to mechanical booster systems. This type is not safe for some applications as steam flashback is possible.

The molecular drag pump (Fig. 8) uses a rotating helical seal to produce the pumping action in shear instead of impingement as in the turbo pump. Now available in a small size, it may be something for the future.

## VACUUM PUMPING SYSTEMS

The performance of a vacuum pumping system depends not only on the pumps employed but also on the piping design, the valving, the gauging and the controls. The following discussion is designed to introduce the designer and user to some of the criteria which should be considered for the various types of vacuum pumping systems. Each application of a system imposes special considerations and requirements.

## VACUUM PUMPING SYSTEM CASH FLOW ANALYSIS (Fig. 13 & 14)

The cumulative cash flow analysis curves show the net costs of owning and operating four types of vacuum systems over a period of 10 years. The capital investment, installation cost, utilities, maintenance, and operating costs, depreciation and taxes are included. The required pumps and controls for a typical 1000 liter/second pumping stack without a vacuum chamber, roughing pumps and gauging were used to estimate the purchase cost. Inflation was assumed at 5% per year, straight line depreciation over the 10 years to zero value is included, 40% tax rate and expensed installation cost are also included.

This type of cash flow is the net cost of ownership after taxes and depreciation. The curves will vary from one installation to another as different experience, type of operation and accounting methods dictate but shows the trends for the diffusion, cryo, turbo and ion pump systems.

The ion pump is most favorable because it is only used below the  $10^{-2}$  Pascal range. This and the fact that they are limited in pumping speed make their application limited. The limited size of turbo pumps makes them impractical for large systems.

The cost difference between the cryo pump and diffusion pump helps explain the popularity of the cryo system in addition to its availability with very high pumping speeds.

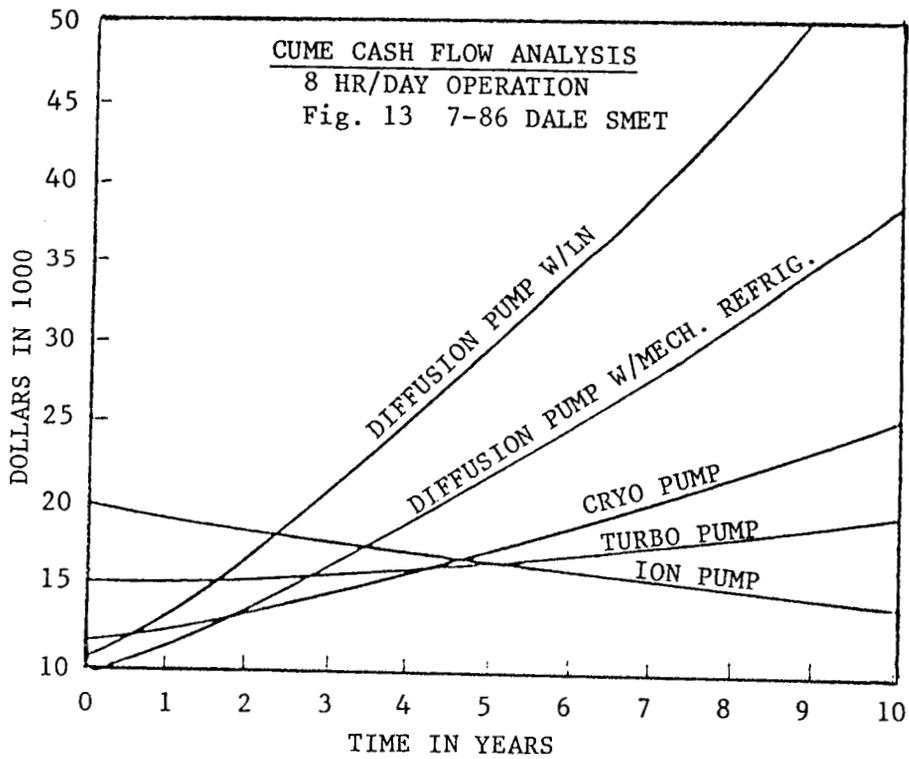
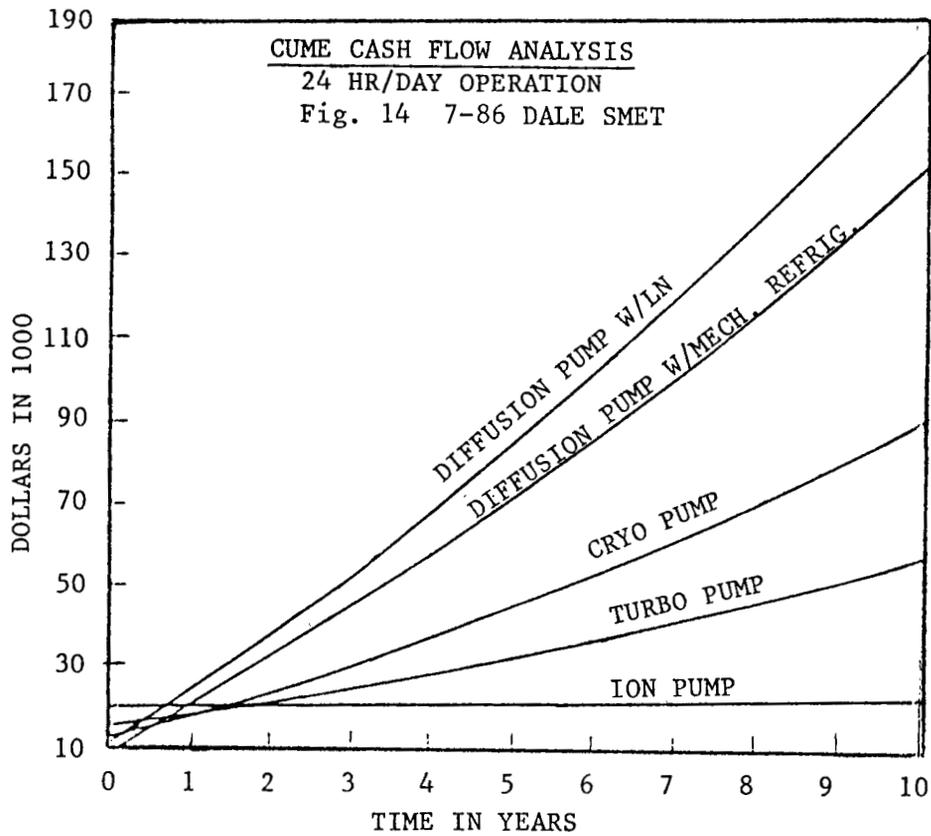
When operating on a continuous basis (7 day, 3 shift) maintenance cost per hour of operation is reduced due to less wear and tear during start-up. Continuous operation yields 4.35 times the production per year compared to a standard 40 hour week. Because of the reduced maintenance, net cost will increase only 4 times for diffusion, 1.5 times for ion, etc. This shows the advantage of operating a production system on a continuous basis.

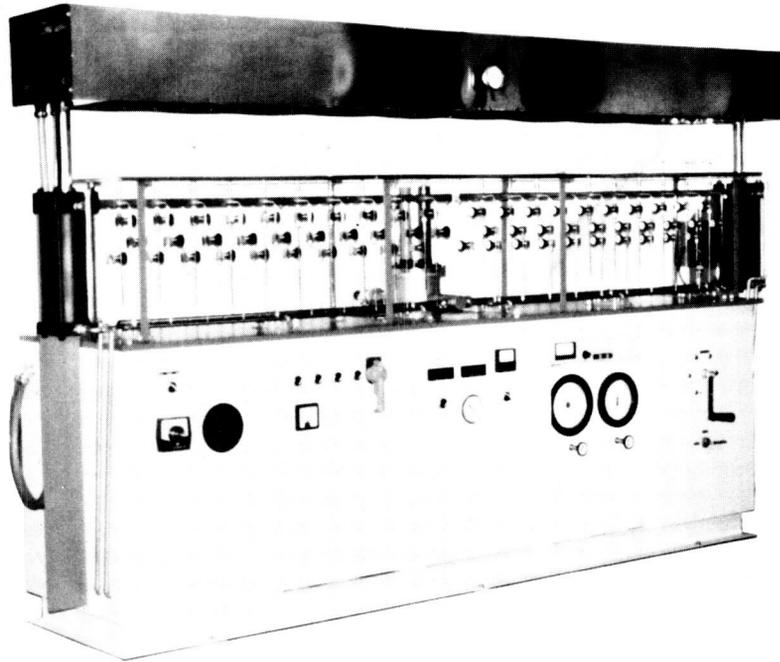
The popularity of the cryo pump is due to the net cost saving as well as performance advantages despite the higher initial capital cost. The cost savings shown for the cryo pump over the diffusion with mechanical refrigeration over the 10 year period on a continuous basis yields a 236% return on the additional \$2,205 cryo system cost. The Internal Rate of Return Method was employed in this calculation.

## DIFFUSION PUMP SYSTEMS

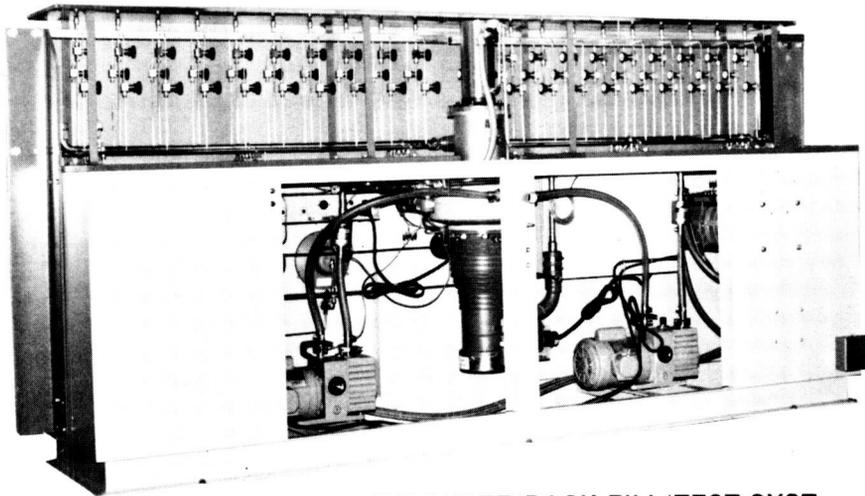
Figure 15 is a 20 port manufacturing system for evacuating, purging, baking, backfilling, pinch-off and leak testing glass plasma display devices. These devices are extremely sensitive to contamination of any sort and reflect the effect of impurities by poor color and shortened life. The liquid nitrogen cold trapped diffusion pump used in this system has proven to be very satisfactory by increasing the excellerated life test of the devices from 500 hours to 1200 hours when compared to the previously employed vacuum processing system.

Various system features contribute to the cleanliness of this system:





OPERATOR SIDE WITH OVEN RAISED



EVACUATE/BACK-FILL/TEST SYST.

SERVICE SIDE SHOWING DIFFUSION PUMP,  
LN COLD TRAP, ROUGHING & BACKING PUMPS

FIG. 15 PROCESSING SYSTEM FOR GLASS  
PLASMA DISPLAY DEVICES

The devices are repetatively evacuated to  $1 \times 10^{-4}$  Pascal and back-filled with an inert gas. The evacuation of this inert gas purges the piping, cold trap and vacuum pumps maintaining the oils in good condition. Each device is evacuated through an 8 mm diameter tube and control valve which provides a relatively high gas velocity during initial evacuation.

The 300 degrees C oven is hydraulically raised and lowered so that it can be raised slowly after the heat cycle and not shock the hot devices with cold room air. The baking process, while evacuating and purging, has been proven in many processes to be the best way and sometimes the only way to assure complete cleanliness of a device.

The diffusion pump and mechanical pumps in this system use the same type of oil. This assures that no cross contamination of the pump oils. The user of this system has banned all silicon oils and greases from his facility as they have been found to be an impossible to remove contaminant.

A roughing pump and a backing pump are included in this system. Using one pump for these two functions can cause excessive backstreaming of the diffusion pump during the period when the foreline valve is closed and the mechanical pump is used to rough the system.

Figure 16 shows a completely automated sputtering system for high production of 5" x 5" substrates. The vacuum pump systems, one at each end of the 9 foot long sputtering chamber, roughs out the entry and exit air locks and maintains the sputtering chamber argon environment in the low  $10^{-1}$  Pascal range. Oil sealed rotary vane type pumps (not shown) and the two diffusion pumps are connected to mechanically refrigerated cold traps. The diffusion pumps are maintained in the  $10^{-4}$  Pascal range by throttling vanes in the suction.

Diffusion pumps are not considered good practice for this application and yet three of these systems produced completely satisfactory titanium thin films for many years on a 3 shift basis. The diffusion pump oil wasn't changed for the first six years of operation and even then it showed little degradation!

This example is given to illustrate that a well designed system, properly operated can give many years of service at low cost. The fact that these pumps were constantly purged with argon probably explains this outstanding performance record which contradicts the cost analysis previously presented.

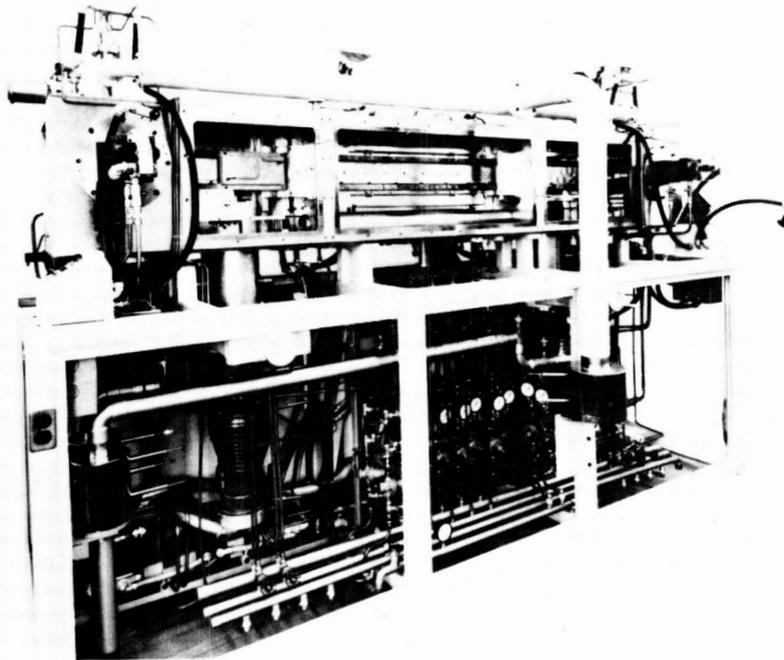
#### CRYOGENIC PUMPING SYSTEM

Figure 17 illustrates a large portable cryo pumping system with a rotary vane pump and Roots blower for roughing. This system was designed to evacuate a group of 34,000 liter chemical reactor chambers to  $1 \times 10^{-3}$  Pascal in less than one hour through 30 feet of 10" pipe without hydrocarbon backstreaming. The system is moved from one reactor to another with a motorized pallet jack and connected to the reactor 10" suction line with a ring clamped, O-ring sealed flange. Pump exhaust, nitrogen and compressed air supplies, power, and central control room computer connections are all made with quick disconnect type fittings. No cooling water is required.

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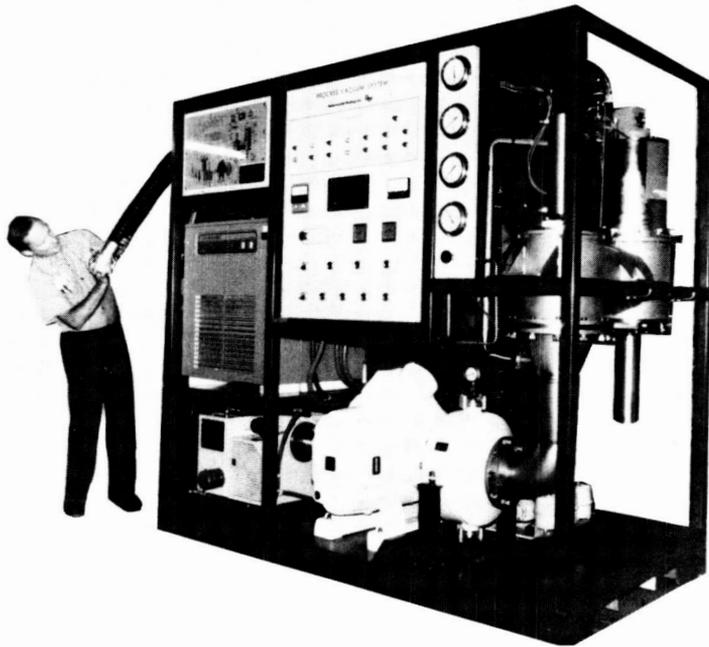
FRONT VIEW: OPERATOR LOADS AND UNLOADS SUBSTRATES



REAR VIEW WITH ACCESS PANELS REMOVED

FIG. 16 DIFFUSION PUMPED SPUTTERING SYSTEM

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SYSTEM ASSEMBLY

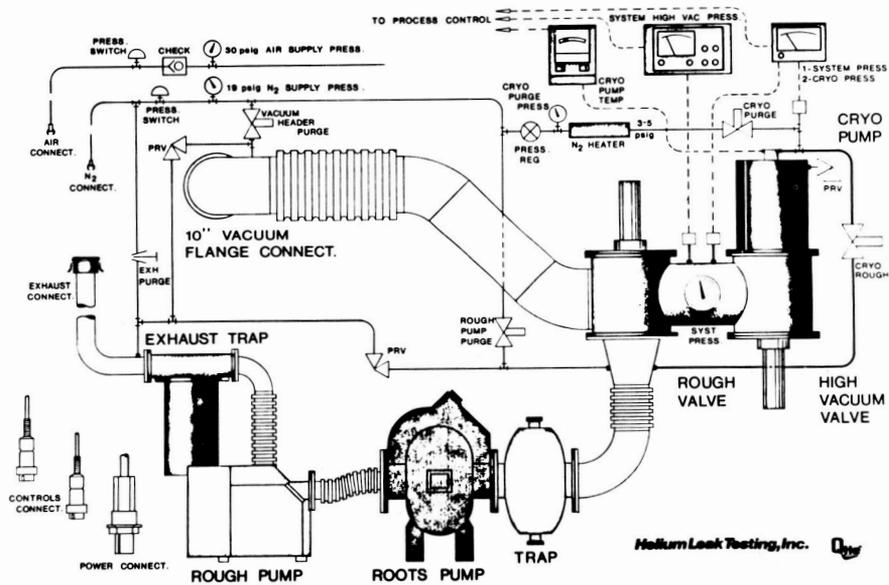


FIG. 17 A CRYO, ROOTS & OIL SEALED  
PORTABLE PUMPING SYSTEM

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The 3" diameter rough pump and 6" diameter Roots pump connections assure that viscous flow is maintained during pump down and a nitrogen purge into the Roots pump suction after blank-off prevents backstreaming. An alumina ball filled trap is added insurance against backstreaming and protects the mechanical pump against the remote possibility that abrasive dust may be evacuated from the reactor. The trap also protects the cryo pump against possible hydrocarbon contamination during regeneration evacuation. This type of trap is usually filled with silica gel but because of its large size, the more shock resistant alumina was used. Silica gel would shatter, settle, and create dust and small particles which might damage the pumps and the settling would provide a bypass channel.

This cryo system is the 2nd generation for the same application; the previous four smaller systems are used to evacuate 1800 liter reactors. A cryo pump system design must protect the cryogenically cooled surfaces against the in-rust of warm air at too high a cross-over pressure which would warm the cold condensing shrouds. If this is allowed to happen, the shrouds will release the previously condensed gases as the refrigeration capacity is small, require a long time to recover pumping speed. The system shown in Figure 17 is able to cross-over at 15 Pascal because it is connected to the large reactor by a conductance limiting suction line (10" diameter x 30'). If the cryo system were directly connected to the chamber, the required cross-over pressure would be much lower.

#### OIL SEALED ROTARY PUMP SYSTEMS

There are probably more oil sealed pump systems in operation than all other types combined when we consider the automated material handling, vacuum packaging and degassing, vacuum hold down, hospital and laboratory, and other commercial and industrial applications. (Don't forget your dentist).

Figure 18 ROTARY OIL SEALED VACUUM  
PUMP WITH DROP-OUT TANK

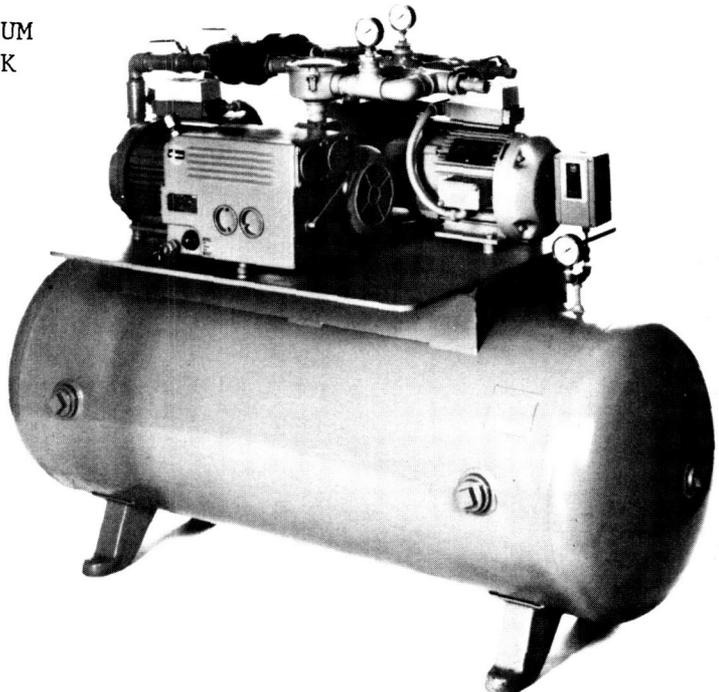


Figure 18 shows a relatively simple method of protecting a vacuum pump in many of these types of applications. The vacuum tank acts not only as a surge tank but also as a drop-out tank for liquids and solid particles which may cause pump maintenance problems. Machine shops using vacuum chucks induct cutting oils and chips into the vacuum suction lines, the hospital operating room is another problem, the electronic circuit board de-soldering and many other applications find this type of vacuum system to be cost effective.

These types of central system applications impose other problems for the standard vacuum pumps. The suction pressure in the system must often be limited to 20" Hg for which specially designed oil sealed pumps are available. Critical applications such as hospitals require redundant pumps and emergency power for reliability. Some applications employ a vacuum pressure switch on the tank or automatic air bleed valves to control the tank at the desired system operating pressure. Time delay of on-off control must be provided to prevent fast cycling the pump.

#### ROOTS PUMP SYSTEM

Figure 19 and 20 show an application of a rotary piston and Roots blower for freeze drying (lyophilization) of food products. This is a severe application as the pumps will be exposed to water vapor, food acid, caustics and oils; the refrigerated condensers are not 100% effective. In spite of this, the system shown has been in operation for 15 years on a one 10 hour run, 5 day per week basis. Each of the two rotary piston pumps and Roots blowers are overhauled approximately every 15 months. A spare of each type is kept on hand so that production is not interrupted during the pump overhaul.

As this system sublimates up to 125 Kilograms of water per run, the problem of condensed moisture in the oil sealed pumps is severe. After trying oil filtration and other methods, it was found cost effective to change the oil after each run. The rotary piston pump is the best choice for this application as it is most tolerant to dust, acid, water vapor and other contaminants.

#### CONCLUDING REMARKS

This discussion of vacuum pumps and vacuum systems is only a brief introduction to the subject. The designer and the user must make an in-depth study of the many types of pumps and systems which are available to determine the most effective and efficient for the process to be performed. As indicated by the cash flow analysis, the lowest first cost system may not be the best investment. It may be necessary to conduct process tests on a pilot basis to help select the best pumping system. There is no substitute for field experience to determine process criteria. A search for experience reports in the same or similar industries will frequently provide valuable data but do not accept "we have done it this way for 20 years and therefore, it is the best way". Vacuum technology is moving ahead and better ways may be available.

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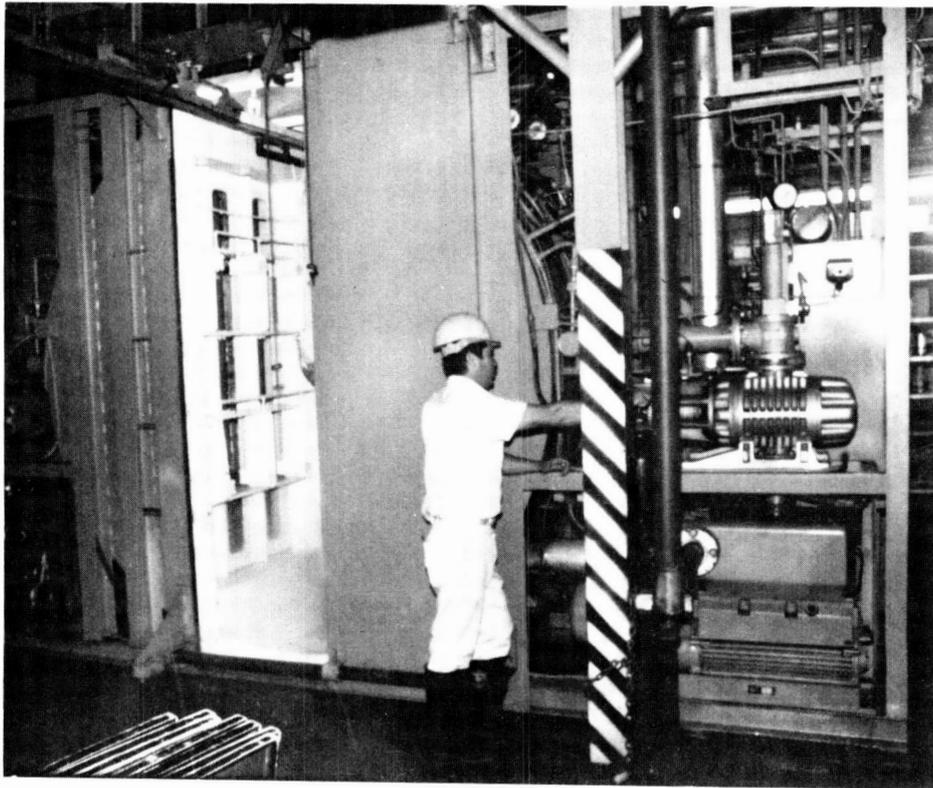


FIG. 19 FRONT VIEW SHOWING CHAMBER ACCESS AND ONE  
ONE SET OF PUMPS

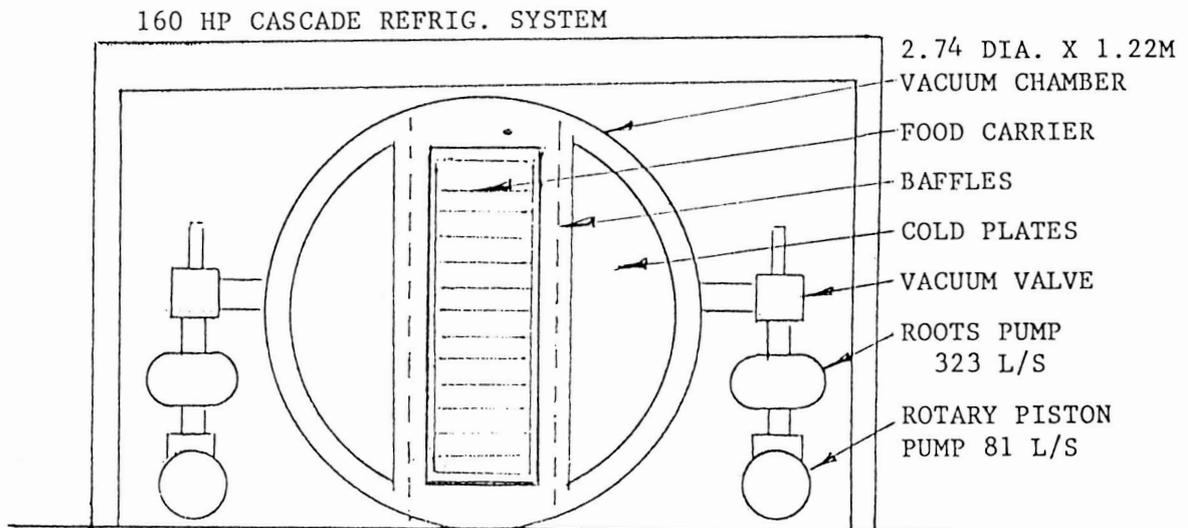


FIG. 20 FOOD FREEZE DRYING SYSTEM SCHEMATIC

## PICTURE CREDITS

The author wishes to thank the following publishers and manufacturers for use of their drawings and photographs.

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